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Battery Powered High Output Voltage Bidirectional Flyback Converter for Cylindrical DEAP Actuator

Lina Huang, Prasanth Thummala, Zhe Zhang, Michael A. E. Andersen

huang@elektro.dtu.dk, pthu@elektro.dtu.dk, zz@elektro.dtu.dk, ma@elektro.dtu.dk

Technical University of Denmark, Department of Electrical Engineering, DK-2800 Kgs. Lyngby, Denmark

ABSTRACT

DEAP (Dielectric Electro Active Polymer) actuator is essentially a capacitive load and can be applied in various actuation occasions. However, high voltage is needed to actuate it. In this paper, a high voltage bidirectional flyback converter with low input voltage is presented. The fundamental operating principle for both energy transfer process and energy recovery process is analyzed in detail. In order to verify the analysis, critical simulation results are provided. So far, a unidirectional flyback converter, which can realize the energy transfer process, has been implemented in the lab. The design parameters for flyback transformer and snubber circuits are illustrated. Moreover, the experimental waveforms are provided.

Index Terms — DEAP actuator, high voltage, flyback, bidirectional

1 INTRODUCTION

DEAP (Dielectric Electro Active Polymer) is a new type of polymer material, which consists of a soft silicone polymer, sandwiched between two compliant metallic electrodes [1]. The similar structure to a capacitor enables DEAP to be fundamentally considered as a capacitive load. Figure 1 shows the measured impedance of DEAP material at low frequency. The -90 degrees phase angle can sufficiently illustrate the capacitive property of DEAP.

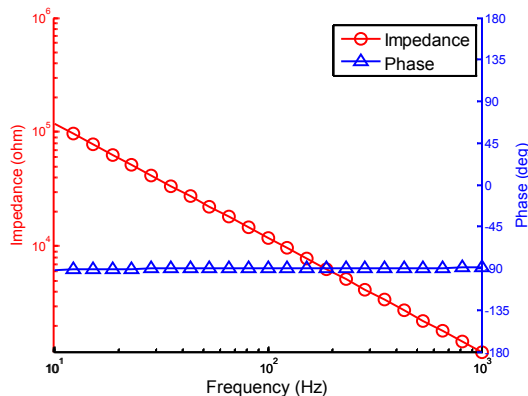


Figure 1. Impedance measurement of DEAP material

When a voltage is applied to DEAP material, the polymer will

compress in thickness and expand in area due to the electric field [2]; therefore, DEAP can be used as an actuator. Compared to traditional electro-magnetic, pneumatic or hydraulic actuators, capacitive actuator possesses many advantages, such as high power density, low weight, fast and direct actuation, high actuating precision, extremely low steady-state power consumption, low noise, etc.

Because of the simple design and immense applicable occasions, cylindrical DEAP actuator, which only performs linear motion, will be an effective replacement for many conventional actuators. Figure 2 shows a cylindrical DEAP actuator [3].



Figure 2. Cylindrical DEAP actuator

The stroke-voltage response of cylindrical DEAP actuator shown in Figure 2, is demonstrated in Figure 3 [4]. It is obvious that DEAP actuator needs high voltage to be fully elongated.

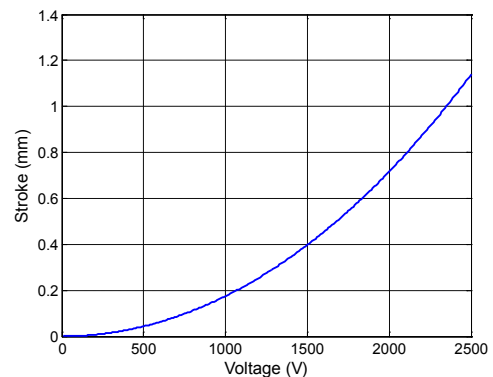


Figure 3. Stroke-voltage characteristic of cylindrical DEAP actuator

Owing to the low weight of DEAP actuator, it can be used in the portable or autonomous systems, where the battery will be the only power source. Therefore, for stimulating DEAP, a DC-DC converter which can convert low input voltage to high output voltage will be necessary. Combined with the capacitive property

of DEAP material and the objective to extend the lifetime of battery, a bidirectional flyback converter can be a good choice, which can not only boost the low voltage to several thousand volts, but also can recover the stored electrical energy when DEAP actuator is released. Furthermore, due to the simple topology of flyback, the converter can be realized in small size, which is vital in the portable or autonomous applications.

This paper analyzes the working principle of bidirectional flyback converter to drive cylindrical DEAP actuator and validates the feasibility through simulation in Section 2. Until now, only the unidirectional flyback converter was realized in the lab, which can boost the output voltage to 2.5kV from a 3V battery and will be addressed in Section 3. And conclusion is drawn in Section 4.

2 BIDIRECTIONAL FLYBACK ANALYSIS

For DEAP actuator, only a small portion of stored electrical energy is converted into mechanical response [5]; therefore, it can approximately be considered as a pure capacitor load in order to simplify the analysis.

2.1 TOPOLOGY AND WORKING PRINCIPLE

The bidirectional flyback converter is shown in Figure 4, consisting of coupled inductors in the middle and active power switches in both primary and secondary side.

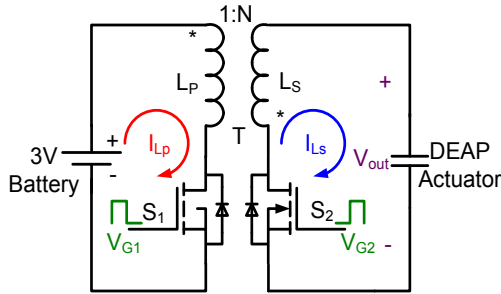


Figure 4. The topology of bidirectional flyback converter

a) Energy transfer process analysis

When driving DEAP actuator, the electrical energy is transferred to capacitive load from battery. Actually, the energy transfer process includes a series of switching cycles. For each cycle, the primary inductor L_P is magnetized in the on-time of S_1 to accumulate magnetic energy. Then in the off-time of S_1 , through body diode of S_2 , the stored energy will be transferred to DEAP actuator from coupled secondary inductor L_S . Ideally, the magnetic energy of L_S is totally transformed into electrical energy in the capacitive actuator. Moreover, based on the basic principle of LC resonant circuit, in every off-time of S_1 , inductor current of L_S and output voltage V_{out} can be expressed in (1) and (2), respectively.

$$\begin{aligned} i_{L_S}(t) &= i_{L_S}(0) \cdot \cos\left(\frac{t}{\sqrt{L_S \cdot C_{DEAP}}}\right) \\ &\quad - V_{out}(0) \cdot \sqrt{\frac{C_{DEAP}}{L_S}} \cdot \sin\left(\frac{t}{\sqrt{L_S \cdot C_{DEAP}}}\right) \end{aligned} \quad (1)$$

$$\begin{aligned} V_{out}(t) &= V_{out}(0) \cdot \cos\left(\frac{t}{\sqrt{L_S \cdot C_{DEAP}}}\right) \\ &\quad + i_{L_S}(0) \cdot \sqrt{\frac{L_S}{C_{DEAP}}} \cdot \sin\left(\frac{t}{\sqrt{L_S \cdot C_{DEAP}}}\right) \end{aligned} \quad (2)$$

where L_S is the inductance of secondary coupled inductor, C_{DEAP} is the capacitance of DEAP actuator, and $i_{L_S}(0)$, $V_{out}(0)$ are the initial current and voltage for inductor and actuator, respectively.

In order to reduce the charge time of fully elongating DEAP actuator and completely transfer the energy stored in the flyback transformer in each cycle, a boundary mode control strategy can be used [6]. When the current through the body diode of S_2 accomplishes freewheeling in the previous cycle, the next cycle immediately starts. In addition, primary peak current control is employed to guarantee the sufficient utilization of magnetic core as well as to avoid its saturation. The fixed input voltage from battery and the application of peak current control make primary conduction time a constant value. However, with the increasing of output voltage, the freewheeling time in secondary side will decrease. That means the switching frequency is variable, and in the early stage of charge, the converter operates in low frequency, whereas at the end, the working frequency becomes high. Although the unfixed operating frequency accelerates the charging process, it also brings some challenges in designing the transformer and analyzing the power loss. The waveforms of first several cycles in charging process are shown in Figure 5.

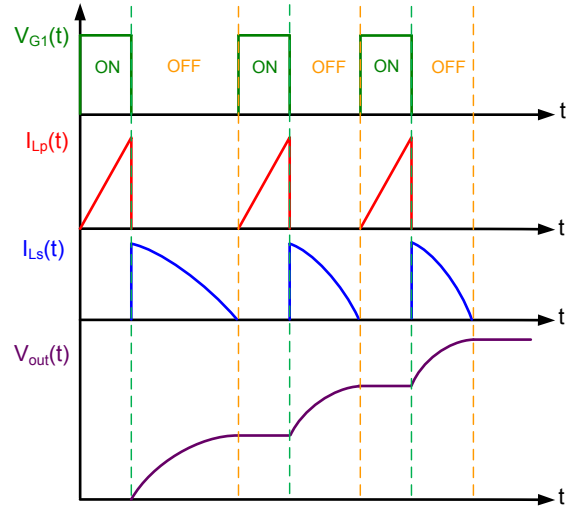


Figure 5. Waveforms in the energy transfer process

b) Energy recovery process analysis

For the purpose of increasing the service life of battery, it is pivotal to recover the energy stored in DEAP actuator when it is released. Like the charge process, the energy recovery process also consists of many successive switching cycles. Only S_2 and the body diode of S_1 work in the discharging process. In each cycle, L_S obtains magnetic energy from DEAP actuator in the on-time of S_2 and releases the stored energy to primary side in the off-time of S_2 .

Similar to energy transfer stage, boundary mode control scheme and secondary peak current control are also adopted in discharge process. The waveforms of first several cycles in the energy recovery process are shown in Figure 6.

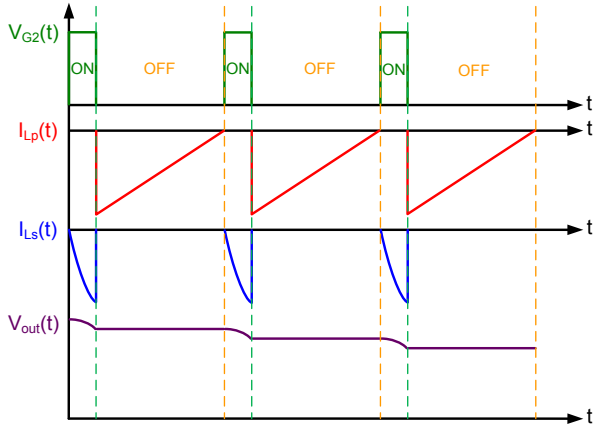


Figure 6. Waveforms in energy recovery process

2.2 SIMULATION VERIFICATION

For validating the analysis mentioned above, a bidirectional flyback converter simulation model has been established with PLECS. In addition, a boundary operation mode and peak current control module is also built up. The detailed simulations parameters are shown in Table 1.

Table 1. Simulation parameters for bidirectional flyback converter

Simulation Parameters	Values
L_p	9 μ H
L_s	21.36 mH
Capacitance of DEAP actuator	142 nF
V_{in}	3 V
Primary peak current	3.9 A
Secondary peak current	80 mA
N	48.7

a) Energy transfer process simulation

Figure 7 shows the whole charge process, in which the output voltage increases from 0 to 2.5kV.

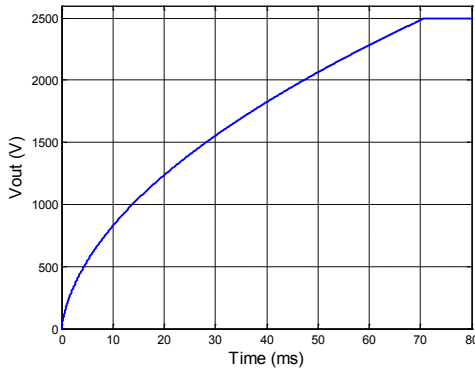


Figure 7. Simulated output voltage waveform in the energy transfer process

In the first several cycles, the current waveforms for both primary and secondary side are shown in Figure 8, which indicates that the boundary mode operation is achieved. Owing to the employment of boundary mode, the charge time is short, only less than 80ms.

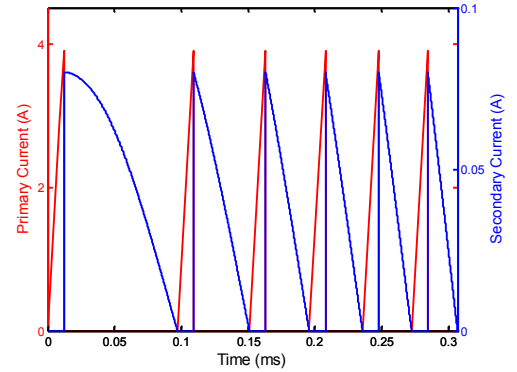


Figure 8. Simulated current waveform in the energy transfer process

b) Energy recovery process simulation

The output voltage decreases from 2.5kV to 0 in the energy recovery process, shown in Figure 9. And the current waveforms are provided in Figure 10, which also demonstrates the realization of boundary mode in discharge process.

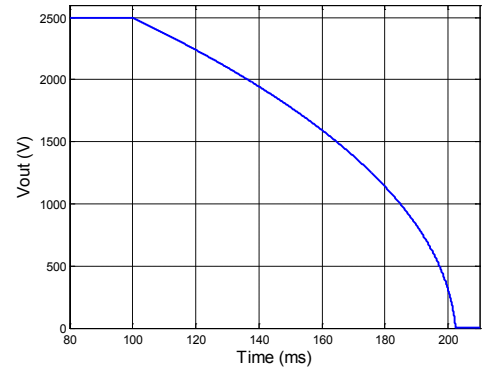


Figure 9. Simulated output voltage waveform in the energy recovery process

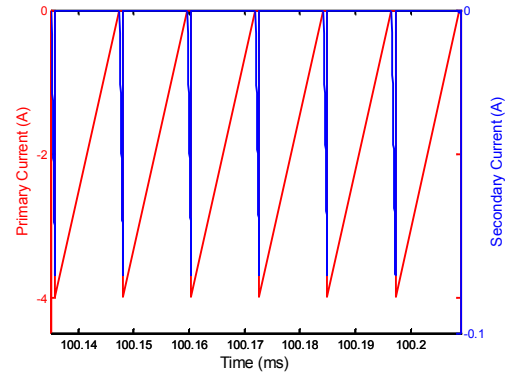


Figure 10. Simulated current waveform in the energy recovery process

3 UNIDIRECTIONAL FLYBACK DESIGN AND REALIZATION

A unidirectional flyback converter to drive DEAP actuator, shown in Figure 11, has been realized in the lab. Because of the voltage stress issue of S_1 , a RC snubber and a RCD clamp circuits are employed [7].

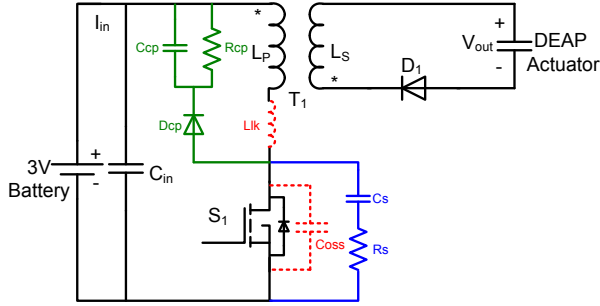


Figure 11. Unidirectional flyback converter

3.1 DESIGN PARAMETERS

The detailed design parameters are shown in Table 2, including the parameters of transformer, RC and RCD circuit.

Table 2. Design parameters for unidirectional flyback converter

Parameters	Values
Turns ratio (primary turns : secondary turns)	7:341
Core type (Core material)	EF20 (N67)
Air gap length	250 μm
L_p	9 μH
L_s	21.36 mH
Leakage inductance L_{lk}	750 nH
Capacitance of DEAP actuator	142 nF
R_s of RC snubber circuit	68.1 Ω
C_s of RC snubber circuit	220 pF
R_{cp} of RCD clamp circuit	20 k Ω
C_{cp} of RCD clamp circuit	1 μF

3.2 EXPERIMENTAL WAVEFORMS

The experimental waveforms are shown in Figure 12, Figure 13 and Figure 14. From Figure 12, it is clear to see the variable switching frequency which is caused by the boundary mode operation.

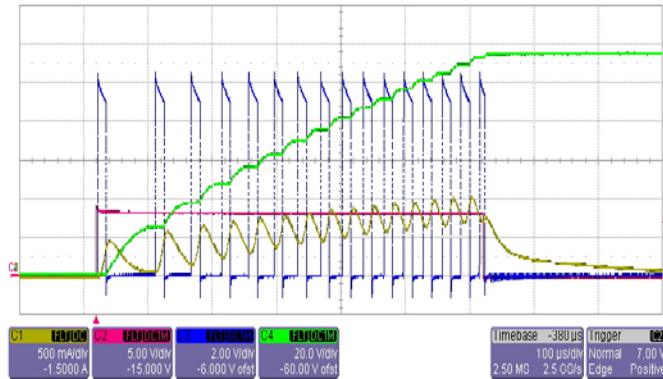


Figure 12. Experimental waveforms (CH1-input current I_{in} ; CH2-charge control signal for converter; CH3-gate signal of S_1 ; CH4-output voltage)

The peak current control can be validated in Figure 13 and the whole energy transfer process is shown in Figure 14.

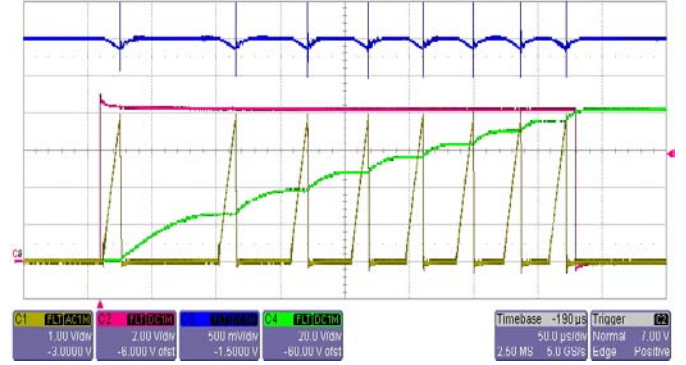


Figure 13. Experimental waveforms (CH1-primary winding current; CH2-charge control signal for converter; CH3-input voltage; CH4-output voltage)

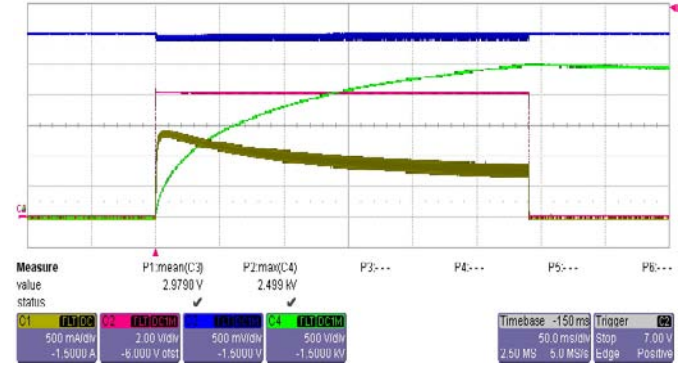


Figure 14. Experimental waveforms (CH1-input current I_{in} ; CH2-charge control signal for converter; CH3-input voltage; CH4-output voltage)

4 CONCLUSION

A high voltage bidirectional flyback converter driving DEAP actuator is presented. The detailed analysis for both the energy transfer and the recovery process is discussed. The simulation results are provided to support analysis. In addition, a unidirectional flyback prototype has been implemented in the lab, which can charge DEAP actuator to 2.5kV.

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